



Project Number: 101147078

Project Acronym: I-UPS

D2.2 – High temperature heat pump sealing selection and optimization

1

Date: 30/09/2025

Author: Enerin

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under agreement No. 101147078. The content of publication is the sole responsibility of the author(s). The European Commission or its services cannot be held responsible for any use that may be made of the information it contains.



This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101147078.



Project Contractual Details

Project Title	Innovative High Temperature Heat Pump for Flexible Industrial Systems
Project Acronym	I-UPS
Grant Agreement No.	101147078
Project Start Date	01/05/2024
Project End Date	30/04/2027
Duration	36 Months
Website	www.I-UPS.eu

Deliverable Details

Number	D2.2
Title	I-UPS HTHP Sealing selection and optimization
Work Package	WP2 – HTHP Adaption, Development & Prototyping
Dissemination Level	Sensitive
Due Date	30/09/2025
Submission Date	01/10/2025
Deliverable Responsible	Enerin
Contributing Author(s)	Arne Høeg, Torgrim Aase(Enerin)
Reviewer(s)	Parth Kumavat
Final Review and Quality Approval	30/09/2025

Document History

Version	Date	Changes	Authors
V1	15/09/2025	First full draft for review	Enerin
V2	30/09/2025	Final version	Enerin





Executive summary

This deliverable, D2.2: High temperature heat pump sealing selection and optimization, has been developed in the context of WP2 under the responsibility of Enerin and collecting inputs from all partners.

The deliverable considers and describes the selection and testing of the high temperature sealing solutions, for the very high temperature application of heating molten salt to 400°C.

The main scope of the deliverable is to identify and test at lower temperatures, several different sealing solutions, all designed for the high-temperature application, to reduce the risk in the testing phase.





Contents

Project Contractual Details	2
Deliverable Details	2
Document History	2
Executive summary	3
Contents	4
1. Introduction	5
2. The HoegTemp Heat Pump	6
3. Design specification	8
3.1 Process simulation	8
3.2 Seal specifications	9
4. Seal selection	10
4.1 Energized polymer seals	10
4.2 O-rings	10
4.3 Gaskets and metal seals	11
4.4 Testing	12
4.5 Selection and optimized design	13
Heat exchanger	13
Cylinder top and gas duct	13
5. Conclusions	14





1. Introduction

This deliverable, D2.2: High temperature heat pump sealing selection and optimization, has been developed in the context of WP2 under the responsibility of Enerin and collecting inputs from all partners.

The deliverable considers and describes the selection and testing of the high-temperature sealing solutions, for the very high temperature application of heating molten salt to 400C.

The main scope of the deliverable is to identify and test at lower temperatures, several different sealing solutions, all designed for the high-temperature application, in order to reduce the risk in the testing phase

Enerin markets and operates a fleet of high-temperature industrial heat pumps (HoegTemp) that are certified for delivering heat at up to 200C. In the EU Horizons project SUSHEAT, the heat pump is upgraded to deliver up to 250C, which is possible within the same conceptual design, heating a pressurized water-circuit.

For heating a molten salt flow to up to 400C, pressurized water is not an option, and the I-UPS project will develop a molten salt heat exchanger for the HoegTemp heat pump. The main sealing challenges are:

1. Flexible seals for the shell-and-tube type heat exchanger between helium and molten salt, to allow for the thermal expansion and the pressure deformation of the parts.
2. Seals for the gas ducts between the hot heat exchangers and the hot cylinder volumes. May or may not need to be flexible
3. Cylinder top seals for the high-temperature cylinder volumes.



2. The HoegTemp Heat Pump

The Enerin HoegTemp industrial heat pump (Fig. 1.) is a 4-circuit double-acting gamma configuration 6-cylinder stirling machine, designed for medium temperatures in the range -100°C to +250°C. The rated heating capacity is 400 kW_{th}, and the maximum heating capacity is above 500 kW_{th}.



Fig. 1. HoegTemp heat pump prototype installed in Enerin’s test cell

Fig. 2. and 3. show the main components of the heat pump. The heat pump consists of 2 cylinder-banks of 3 cylinders (D1, W12, D2), with 2 sets of heat exchangers bolted on to the sides of the cylinders. Each cylinder bank is an independent circuit pair, and the circuits are separated by the power piston in the middle (power) cylinder (W12). The circuits are slightly different, in that the power piston separates the hot gas volume in one circuit (1) from the cold gas volume in the other circuit (2).

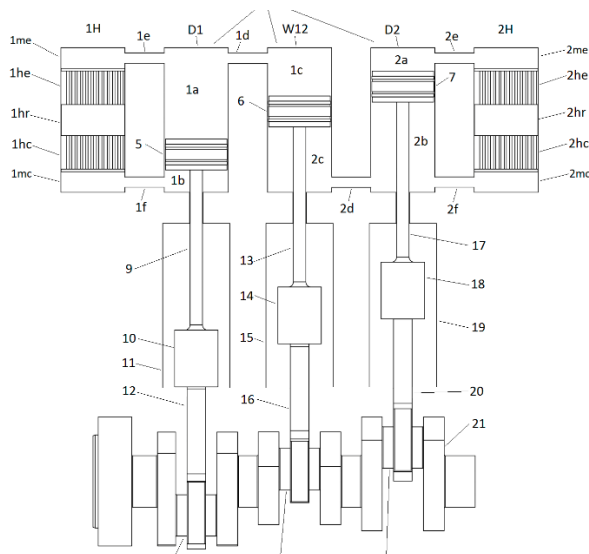


Fig. 2. Configuration tested at IVAR, GE and Pelagia

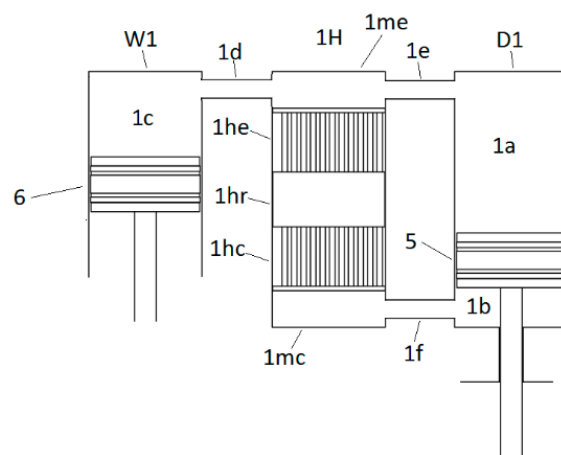


Fig. 3. High-temperature seal positions: W1, 1d, 1he, 1e, D1



Each heat exchanger module consists of 3 heat exchangers: a tubular heat exchanger (1hc) between helium and the low-temperature heat source at the bottom, a regenerative heat exchanger (1hr) that stores heat from the helium in a stainless-steel mesh in the middle, and a tubular heat exchanger (1he) between the helium and the high-temperature (sink) water-circuit at the top.



3. Design specification

3.1 Process simulation

A modified configuration has been chosen for future high-temperature heat pumps, where the compression and expansion work is done on low-temperature gas, shown in Fig. 4. For the I-UPS test campaign, a 1-circuit version of the future configuration has been developed, based on existing design components, combined with the new heat exchanger from WP3, shown in Fig. 5.

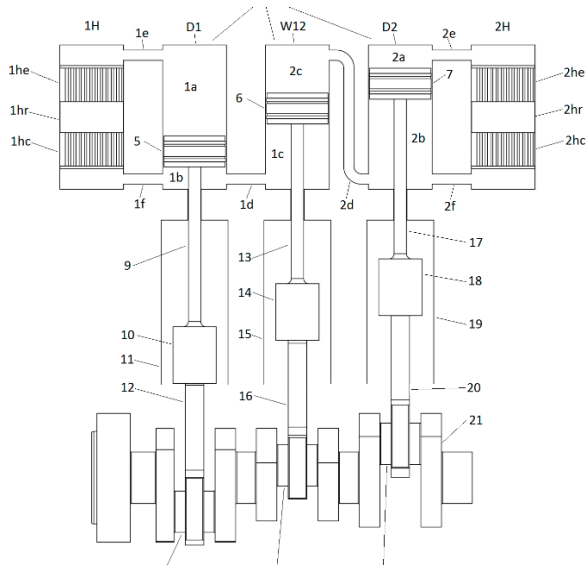


Fig. 4. Configuration for future high-temperature heat pumps

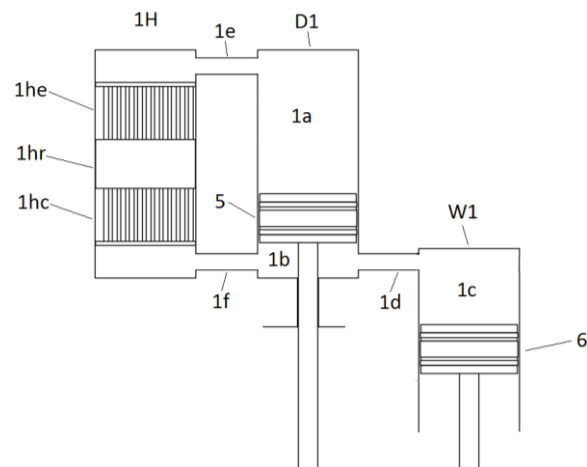


Fig. 5. A simplified lay-out has been chosen for the I-UPS test. High-temperature seal positions: 1he, 1e, D1

For the high-temperature application, the heat pump will be made with only one heat exchanger module per circuit, placed on one side of the cylinder bank, so the gas ducts may be placed on the other side of the cylinder bank. This is primarily done to achieve a higher compression ratio than with the standard configuration, but also to reduce prototype cost. In a commercial heat pump, the higher compression ratio could alternatively be achieved with a larger cylinder swept volume. It may be that the compression ratio will be a trade-off between heating capacity, efficiency and seal temperatures.

High-temperature heat is generated as hot gas in volume 1a is adiabatically compressed by a volume reduction in volume 1c, and the heat is transferred to the heat transfer medium in the heat exchanger 1he.

The most challenging seals are between the heat exchanger 1he and the housing, in the duct 1e and in cylinder D1, sealing off the volume 1a.

In the tested heat pumps, there is an additional 1d.



The I-UPS preliminary design has been modelled using the SAGE simulation software, with the design capacity, along with the full-scale full-power future commercial heat pump. The tested configuration is also separately modelled.

Process parameters:

- Source temperature: 40°C
- Sink temperatures: 150°, 200°, 250°, 300°, 350°, 400°C

At each sink temperature level, the seal temperatures at 1a, 1e and 1he is simulated.

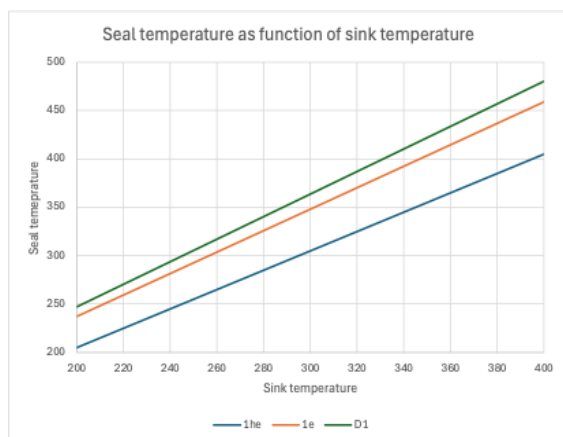


Fig. 6. Seal temperatures as function of sink temperature for full-scale heat pump

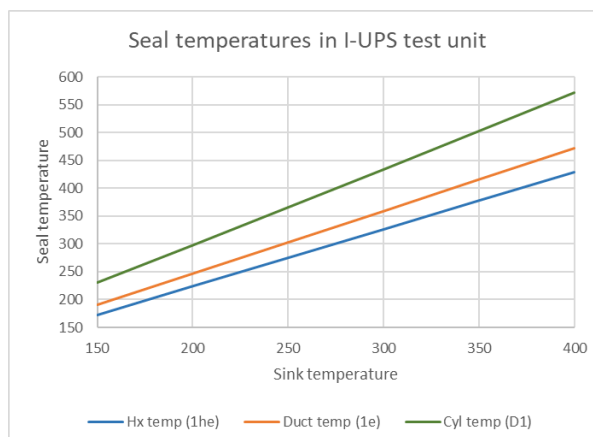


Fig. 7. Seal temperatures as function of sink temperature for I-UPS test unit

3.2 Seal specifications

The seals for the full-size commercial heat pump will experience temperatures up to 80C higher than the sink temperature, while the prototype test unit in the I-UPS project will experience seal temperatures up to 170 C higher than the sink temperature. This represents a challenge, but also an opportunity, in that prototype testing may qualify the seals for higher sink temperatures in commercial applications.

Table 1. Seal temperatures as function of sink temperature for full-scale and test heat pump

Seal	Unit/temp:	V6 300°C	V6 400°C	I-UPS 300°C	I-UPS 400°C
Hx seal		310	410	325	430
Duct seal		350	460	360	470
Cyl top seal		370	480	430	570

Common for the seals is that the internal pressure is up to 80 bar, with a pressure amplitude of 20 bar at a frequency of up to 16 Hz.





4. Seal selection

In addition to sealing high-pressure helium at elevated temperatures, the seals must also adapt to movement of the heat exchangers relative to the heat exchanger housings due to changes in pressure and temperature, movement or misalignment between heat exchanger housings and cylinders, and deflection of cylinder lids relative to the cylinder itself.

Helium will leak through the tiniest imperfections, and helium will diffuse through the solid materials, especially through polymers and elastomers, but even through metals.

The seals will be opened during maintenance of the heat pump, and sealing surfaces may be worn during assembly and disassembly. The seals will be exposed to detergents during cleaning, and oil contamination as well as dust from polymer piston rings.

Sealing selection is based on the following criteria:

- Sealing performance at the expected operating temperatures: Direct leaks and diffusion
- Seal operating life at expected operating temperatures
- Seal sensitivity and robustness
- Reusability of the seals
- Seal price and availability

4.1 Energized polymer seals

Lip type seals made from high-temperature polymer compounds, with metal spring loading for dependable sealing. These seals are engineered to each application, and our supplier recommends a compound they have rated to 350°C: 'Proprietary PTFE. Good sealing capabilities at elevated temperatures and excellent for static or low dynamic service.' In principle, we see no barrier to designing similar seals from high-tech engineering polymers such as polyimide compounds (PI). PI is very expensive, and the solution should be verified with standard compounds first and then swapped for PI. We have quoted PI material for € 1000 per 10 mm, good for machining 1 seal, while similarly sized energized seals in PTFE compounds are available at around € 200 per seal. The energized seals are expected to be reused and last for several years in operation, maybe even the lifetime of the heat pump, for some positions.

4.2 O-rings

The newest FFKM compounds for high-temperature O-rings are reasonably good at temperatures up to 370°C. Two important performance metrics, compression set and sealing force retention at high temperatures, are shown in Fig. 8. and Fig. 9. The biggest drawback is the price, which is in the region of € 1000 per seal. The second biggest drawback is the operating time, which is in the hundreds of hours, not in the tens of thousands. Non-brand



FFKM O-rings are available at around € 100-200 per seal, while standard FKM O-rings are available at around € 30-50, depending on the size.

Compression Set vs. Time at 204°C (400°F)

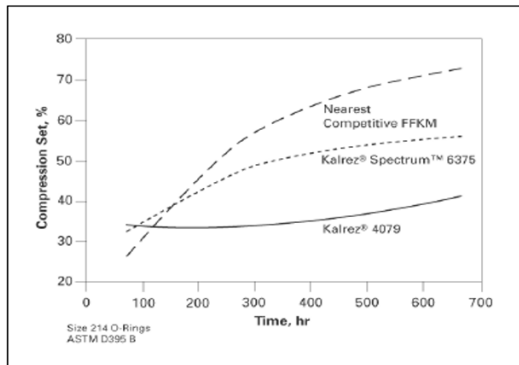


Fig. 8. Compression set of FFKM O-rings

Sealing Force retention at 204° C

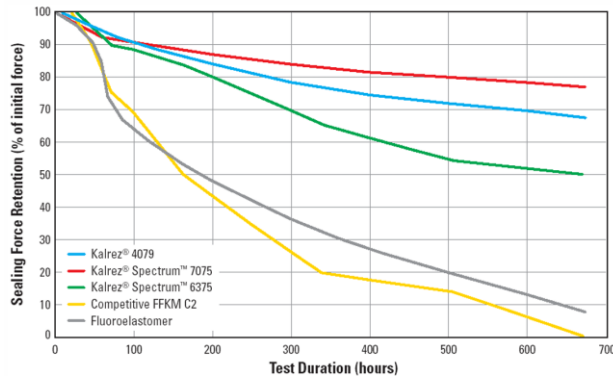


Fig. 9. Sealing force retention for FFKM O-rings

4.3 Gaskets and metal seals

Flexitallic has a good overview of high-temperature seals for hydrogen, which is even more difficult to seal than helium. From Flexitallic¹, both semi-metallic and metal seals should be ok for the application. The normal seal metals are copper, steel and aluminium. For semi-metallic seals, graphite or vermiculite would be good options.

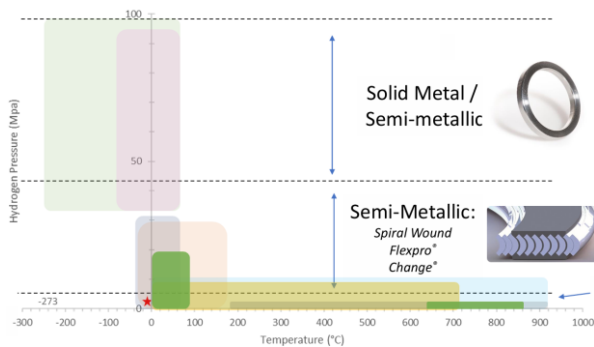


Fig. 10. Operating domains of metallic and semi-metallic seals

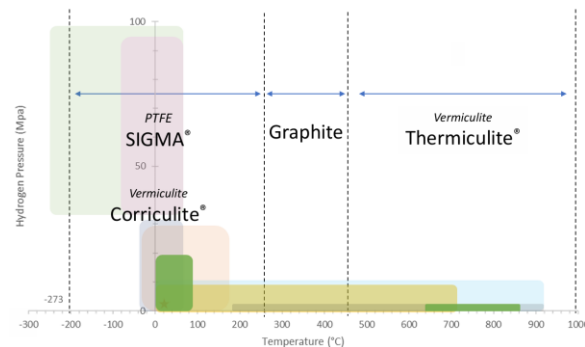


Fig. 11. Operating domains of PTFE, graphite and vermiculite seals

Seal should be designed for a gasket pressure of at least 20 MPa with vermiculite, preferably 60 MPa. Preferably 80 MPa with graphite. Testing in another R&D project found that metal seals require almost uniform pressure.

We have not yet received quotes for high-temperature gaskets, while simple gaskets typically cost in the range of € 10 for single-use gaskets.

4.4 Testing

High-temperature testing in Enerin’s test rig has been conducted during the summer of 2025. The test rig is limited to 200°C sink temperature, while the seals are exposed to the higher temperature of the refrigerant. Figure 12 shows the temperatures experienced by the high-temperature seals during high-temperature endurance testing from 160°-200°C in the summer of 2025. The test period includes some testing at lower temperatures, as the heat pump was delivering heat to the pilot customer’s regular production.

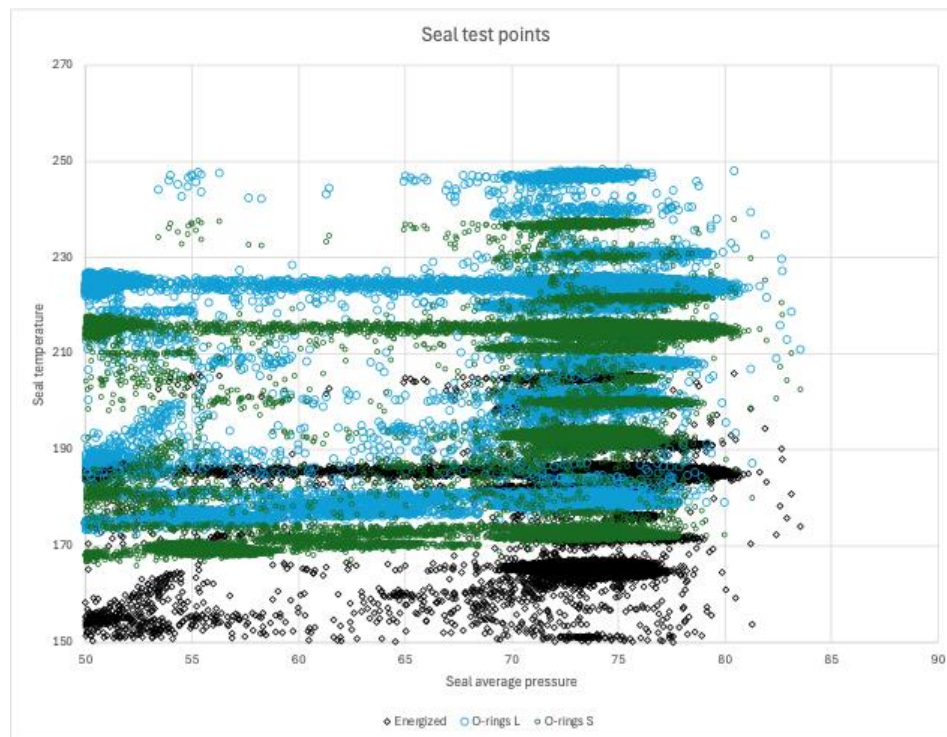


Fig. 12. Test points for seals tested at high temperature in Enerin’s test rig. Chart over individual sealing positions at different combinations of temperature and pressure. The duct seals (1e) are referred to as O-rings S, while the cylinder top seals (D1) are referred to as O-rings L in this chart.

During the endurance testing, the following seals have been tested for more than 800 hours:

- Hx seals (1he): 32 energized polymer seals tested with no performance issues.
- Duct seals (1e): 12 FFKM O-rings (O-rings S) tested. Slight deformation measured, deemed ok for re-use.
- Cylinder seals (D1): 6 FFKM O-rings (O-rings L) tested. Slight deformation measured, deemed ok for re-use.

In another EU Horizons project, copper gaskets have been tested, with OK results at lower pressures and temperatures. The results led to a redesign of the seal interfaces in the I-UPS project.

4.5 Selection and optimized design

Heat exchanger

Energized polymer seals and FFKM are the only solutions identified so far, that are able to withstand the movement and thermal expansion between the heat exchanger and the housings. The groove is shown in Figure 13.

- Energized seals with 350°C temperature limit.
- Alternative solution O-rings with temperature limit 370°C for 600 hours.
- Possible future solution energized seals made from PI or other high-temperature polymer (fluor free) to achieve 400°C.



Groove:

- 8.5 mm long in the axial dimension,
- 4.75 mm in the radial direction.
- Surface finish Ra 0.1-0.2

Fig. 13. Detail of Hx seal grooves.

Cylinder top and gas duct

The cylinder top seal and gas duct seal are exposed to similar temperatures, and the other design requirements are also similar. For both seal positions, the components are designed to accommodate 3 different sealing solutions, that all have the potential to work in the very high temperatures in the I-UPS project (Fig. 14. and 15.):

1. Energized polymer seal: standard compounds rated to 350°C, potential for switching to PI for 400°C.
2. FFKM O-ring. Best compound for the application is rated to 370°C for 600 hours. May last longer than that if not disturbed
3. Plane gasket. Rated to sufficiently high temperatures.

The components have been redesigned to accommodate all three solutions, and the bolt interfaces have been upgraded to provide even contact pressure for gaskets.

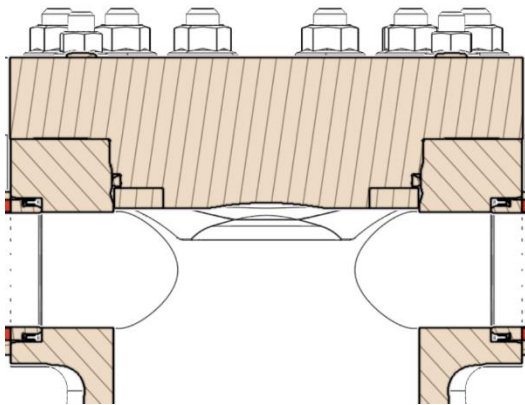


Fig. 14. Cross section through cylinder top seal and gas duct seals

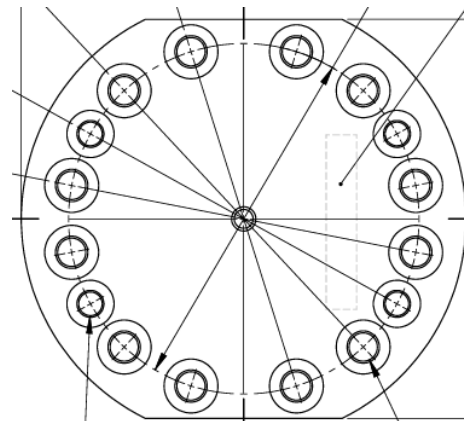


Fig. 15. Updated bolt interface

The previous cylinder top interface with 775 kN combined bolt force, with up to 76° between bolts, was tested to perform ok with metal gaskets up to approximately 60 bar. The revised interface has increased the combined bolt force by 26% and reduced the largest bolt spacing to 35°. The changes should be sufficient to allow the use of metal gaskets up to the design pressure of 80 bar.

Both sealing positions will have grooves 8.5 mm long in the axial direction, 4.5-4.75 mm in the radial direction. Surface finish Ra 0.1-0.2. In addition, both positions will have planar surfaces, 7-11 mm wide in the radial direction, with Ra 0.2-0.4 surface finish, and evenly distributed contact pressure.

5. Conclusions

This deliverable, D2.2: High temperature heat pump sealing selection and optimization, has been developed in the context of WP2 under the responsibility of Enerin and collecting inputs from all partners.

The deliverable considers and describes the selection and testing of the high temperature sealing solutions, for the very high temperature application of heating molten salt to 400°C. The main scope of the deliverable is to identify and test at lower temperatures, several different sealing solutions, all designed for the high-temperature application, to reduce the risk in the testing phase.

Realistic sealing solutions were identified for 2 of the positions to achieve sink temperatures of 400°C, while the third will initially be good for 370°C, with a potential upgrade to 400°C.

The optimized seal design has been implemented in the components designed and ready for production for the prototype

ⁱ Flexitallic, Introduction to hydrogen sealing